The Longitudinal and Transverse Beam Dynamics Simulation in the MMF Storage Ring

V.A. Moiseev
Institute for Nuclear Research of the Academy of Sciences
60-th October Anniversary Prospect, 7a, Moscow 117312, Russia

Abstract

The computer code has been developed to study both longitudinal and transverse microwave instability problems of an intense beam in synchrotrons and storage rings. The macroparticle method and impedance beam-environment interaction are used in simulation. The beam dynamics have been explored for the Moscow Meson Factory (MMF) storage ring at slow extraction operation mode (SEM). Some results of the numerical simulation are presented.

I INTRODUCTION

The slow extraction mode of the MMF proton storage ring was designed to transform the bunched beam structure during $100\mu s$ accelerator macroimpulse to uniform beam ejected between two successive macroimpulses ($\sim 9.9ms$) [1].

For SEM the ring and beam parameters are [3]:

total intensity	$3.12 \cdot 10^{13} ppp$
average current	$11.3\ A$
relativistic parameters	$\beta = 0.792$ $\gamma = 1.639$
linac rf frequency	$f_{rf} = 198.2\ MHz$
total momentum spread	0.002
transition energy	$\gamma_{tr} = 1.720$
momentum slip factor	$\eta_0 = (1/\gamma_{tr}^2 - 1/\gamma^2) = -0.35 \cdot 10^{-1}$
chromaticity	$\xi = -0.534$
revolution period	$T_r \approx 450ns$
betatron tunes	$Q_x = 1.875$ $Q_y = 1.915$

In the present case the nominal particle energy is below the transition energy. Therefore the capacitive behaviour of the beam- storage ring interaction in the smooth vacuum chamber is expected. But with the space charge dominated impedance the stability of the particle motion might be a problem. However due to operation near transition energy it could be achieved sufficiently long growth time for the instabilities.

II SIMULATION MODEL

Because the changes of the transverse particle parameters are faster then of longitudinal ones the longitudinal dynamics has been taken as basic. The tracking procedure used for longitudinal motion simulation for the MMF storage ring was described in ref.[2].

In betatron phase space $(x_\beta; \dot{x}_\beta)$ the particle motion is governed by differential equation [4]:

$$\ddot{x}_\beta + \dot{\varphi} x_\beta = \frac{F(t,\theta)}{m_0 \gamma} \quad (1)$$

$$\dot{\varphi} = Q_0 \omega_0 (1 - \dot{\tau}) + \omega_\xi \dot{\tau} \quad (2)$$

here x_β and $\dot{x}_\beta = dx_\beta/dt$ are the transverse particle coordinate and velocity with respect to the equlibrium orbit; Q_0 is Q_x or Q_y; $\omega_0 = 2\pi/T_r$; $\dot{\tau} = \eta(dp/p)$; $\omega_\xi = Q_0\omega_0\xi/\eta_0$. Induced electromagnetic force is defined [4]

$$F(t,\theta) = -\frac{i\beta_0}{2\pi R}\int_{-\infty}^{\infty} Z_{tr}(\omega) S_{tr}(\omega,\theta) e^{i\omega t} d\omega \quad (3)$$

$$Z_{tr}(\omega) = Z_{trsc}(\omega) + Z_{trrw}(\omega) + Z_{trbb}(\omega) \quad (4)$$

Here $Z_{trsc}, Z_{trrw}, Z_{trbb}$ are the transverse space charge, resistive wall and broad band impedances defined by standard formulas [4]. And S_{tr} is Fourier spectrum of the transverse dipole-moment current. Appling the macroparticle beam representation and the binning technique which has been used for longitudinal dynamics simulation all spectrum amplitudes of S_{tr} can be determined. Due to computer capability only horisontal transverse motion was studied.

The model parameters are: the total number of macroparticles $N \sim 80000$, the broad band shunt resistance $R_{sh}/n_r = 50\Omega$ and the other parameters are the same which were used for longitudinal dynamics simulation [2].

To estimate the growth time for unstable harmonics the spline approximation for the macroparticle momentum distribution and then the dispersion integral calculation [4] were carried out.

III SIMULATION RESULTS

A Longitudinal Dynamics

In fig.1 the normalized momentum distribution function is shown at the end of injection ($113\mu s$) and during circulation ($165\mu s$ and $215\mu s$). For total stored beam intensity at the begining of circulation a lot of longitudinal density harmonics close to $mT_r f_{rf} \approx 89m$, where m is integer, have essential growth. The theoretical growth time for these harmonics is $30 \cdots 100\mu s$. At the end of injection the momentum spread is insufficient to suppress the microwave instability by Landau damping. During injection the change of the momentum distribution function is negligible, but further the low energy tail of the momentum distribution function is developed drasticly. That turns on effectively the Landau damping and leads to saturation of amplitude growth for unstable harmonics. For stabilization the small number of particles is needed in the momentum tail for low energy intense beams with space charge dominated impedance [5]. In our simulation the saturation times for unstable harmonics are

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$50 \cdots 80 \mu s$. Further all harmonics which have had the essential growth are damped. Unfortunetly the ring design parameters restrict the momentum deviation on the value $(\Delta p/p) = -0.75 \cdot 10^{-2}$. That can cause the loses of the particles with lowest energy if the Landau damping will be weak to suppress the unstable harmonics.

Since for simulation the over-pessimistic value for broad band shunt resistance was chozen it has been made the growth time calculation for unstable harmonics for $R_{sh}/n_r = 5\Omega$ expected for MMF storage ring. The particle momentum distribution function which has been resulted from simulation before beam loses (curve for $215 \mu s$ in fig.1) was used. The growth times calculated are greater than $20ms$. In fig.2 the instability curve with growth time $24ms$ and operation impedance for azimuthal harmonic $n = 267$ are shown. For expected ring impedance parameters the simulation results have shown the possibility to avoid beam loses due to the longitudinal microwave instability because of the characteristic times the particles reach the wall are much more the extraction time. Moreover, beam stored current drops linearly with time.

B Transverse Dynamics

In fig.4 the normalized betatron amplitude distribution, the betatron phase space projection and view of the betatron particle distribution function are shown. Here $x = x_\beta; x_p = \dot{x}_\beta / Q_0 \omega_0; A_x = \sqrt{x^2 + x_p^2}$. It is evidence that during total stored beam circulation there is rebuilding of the particle distribution function which causes the global changes of the Fourier spectrum of the transverse dipole-moment current. The beam size increasing due to the process mentioned above is not dramatic and can be considered as small addition to beam size growth due to changes of the momentum distribution function.

The growth time calculated for more dangerous low frequency harmonic n=2 by standard theory [4] is $\sim 1ms$ at the end of injection ($113\mu s$) and $\sim 1.6ms$ at the end of simulation ($215\mu s$). Therefore it may be expected there will not problem with transverse stability in the low frequency range for SEM storage ring operation. However if $\eta \rightarrow 0$ the threshold values for transverse impedance will be slightly differ for any harmonics of the dipole-moment current. It means the Landau damping is not effective for that harmonic which has the large value of ReZ_{tr}. Because the great shunt resistance of broad band impedance was chosen for simulation the growth time for high frequency harmonics is less the one for the low frequency range. In fig.3 instability curve with growth time $33\mu s$ and the impedance parameters are shown for harmonic n=450. That situation is dangerous and can result in the transverse beam blow-up on high frequency range for storage rings working in quasi-isochronous mode. However, taking into consideration the over-pessimistic value of the broad band shunt resistance, the dependence of the particle betatron frequency (2) from betatron amplitude and the possibility to change the ring chromaticity the growth time for high frequency harmonics may be done greater the calculated above.

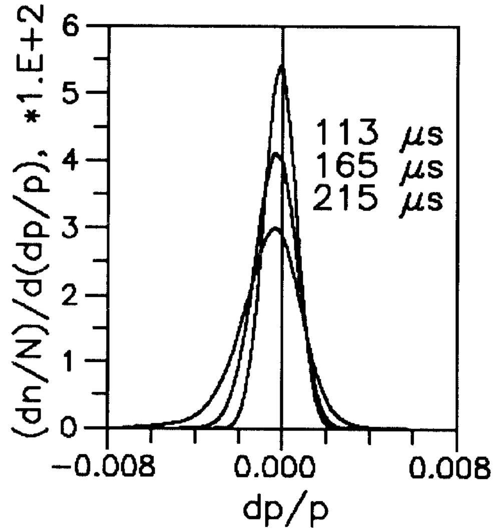

Figure 1: The change of momentum distribution.

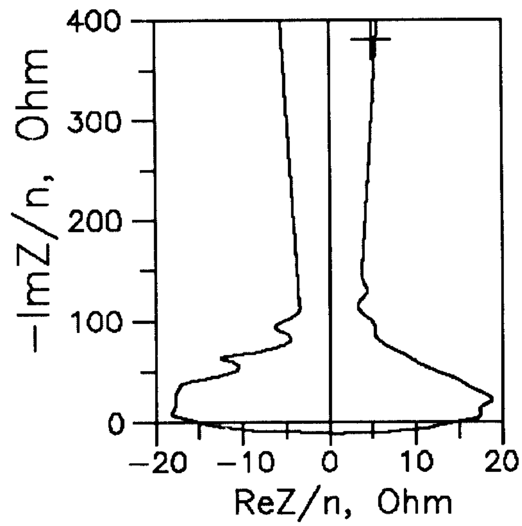

Figure 2: Longitudinal instability diagram for n=267.

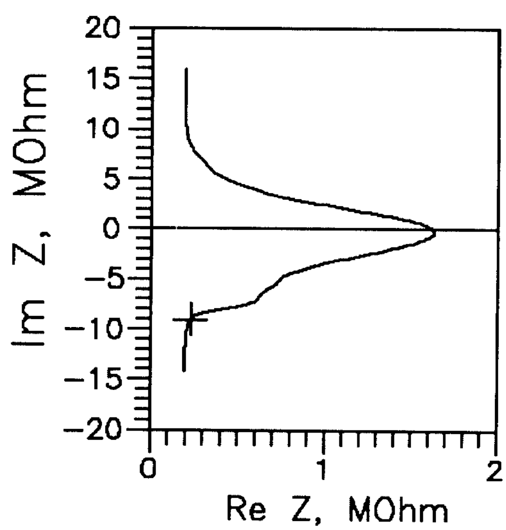

Figure 3: Transverse instability diagram for n=450.

The main results of the transverse particle dynamics simulation are the particle re-distribution in the betatron phase space and high frequency transverse microwave instability. The first effect should be taken into account, but second must be cure by adjusting the ring multipole correction elements and eliminating the strong wide-band parasitic resonators in the high frequency domain.

IV REFERENCES

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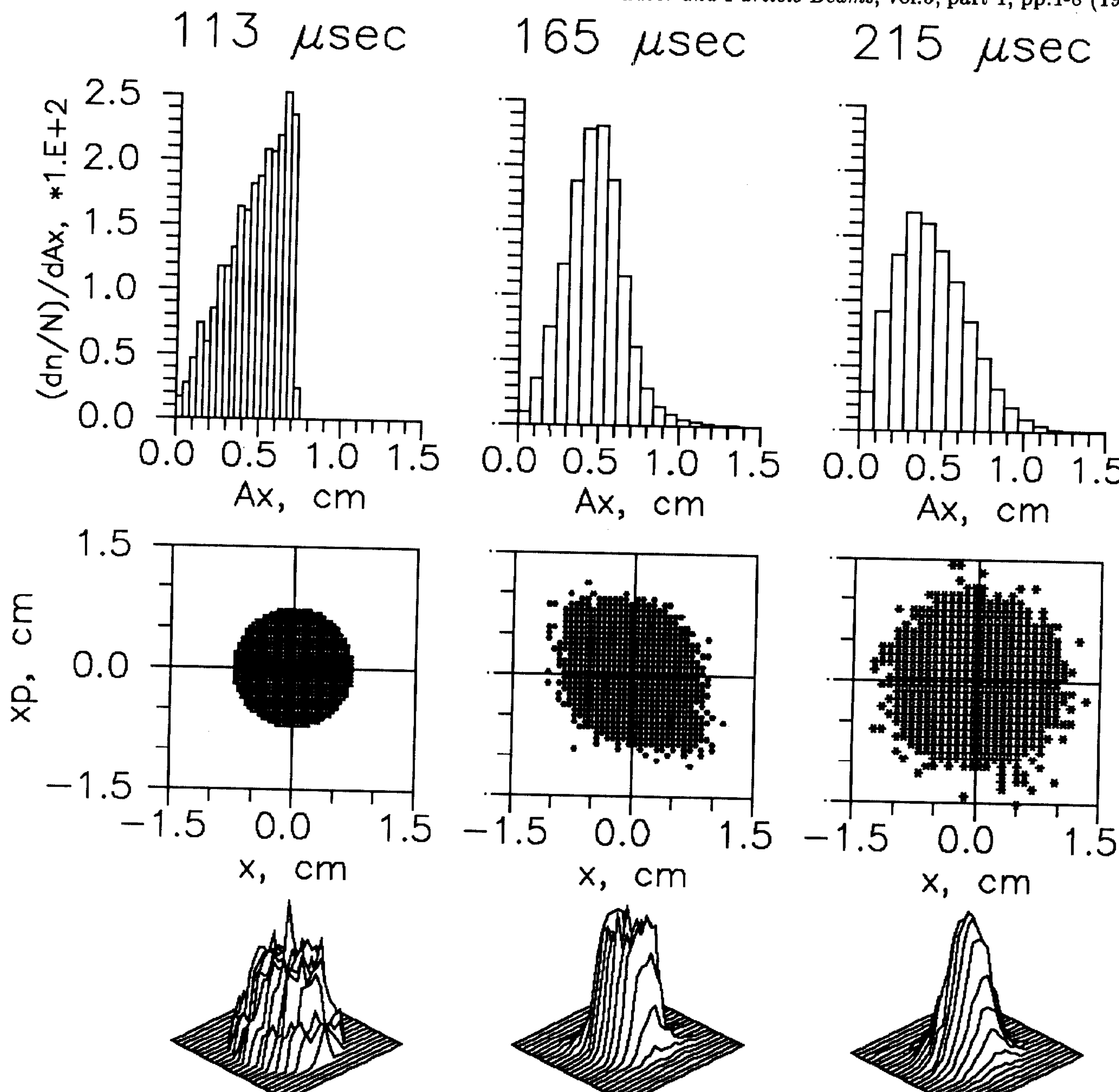

Figure 4: Betatron amplitude distribution, betatron phase space projection, view of the betatron particle distribution function.